

NASA'S SPACE LAUNCH SYSTEM TAKES SHAPE

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Figure 1: Artist rendering of SLS rollout from Vehicle Assembly Building, Kennedy Space Center.

ABSTRACT

Significant hardware and software for NASA's Space Launch System (SLS) began rolling off assembly lines in 2016, setting the stage for critical testing in 2017 and the launch of new capability for deep-space human exploration. (Figure 1) At NASA's Michoud Assembly Facility (MAF) near New Orleans, LA, full-scale test articles are being joined by flight hardware. Structural test stands are nearing completion at NASA's Marshall Space Flight Center (MSFC), Huntsville, AL. An SLS booster solid rocket motor underwent test firing, while flight motor segments were cast. An RS-25 and Engine Control Unit (ECU) for early SLS flights were tested at NASA's Stennis Space Center (SSC). The upper stage for the first flight was completed, and NASA completed Preliminary Design Review (PDR) for a new, powerful upper stage. The pace of production and testing is expected to increase in 2017. This paper will discuss the technical and programmatic highlights and challenges of 2016 and look ahead to plans for 2017.

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INTRODUCTION

Since the end of the Apollo missions to the moon in the early 1970s, NASA's human spaceflight efforts have focused on operations in low Earth orbit (LEO). Insights gained have been enormous, encompassing materials, structures, technology, microgravity, radiation and other space environments, human health, operations and maintenance, extravehicular activity (EVA), robotics, science operations, ground support, launch and landing and many other areas. NASA is now prepared to take that experience and venture beyond Earth orbit again to the moon, Mars and beyond. The challenges are as vast and unprecedented as the distances involved. NASA is taking the first steps by developing a transportation system to meet those challenges – the Space Launch System (SLS).

The SLS Program was created in 2011. Affordability was a key goal from the start. Evolvability would allow the vehicle to increase capability as missions became more demanding without redesigning the vehicle. Safety and reliability were considered as part of overall mission architecture, not just a vehicle consideration. After trading thousands of possible configurations, NASA selected a heavy-lift vehicle based on the powerful and proven space shuttle liquid fuel main engines and solid fuel boosters with a new core stage design. The initial Block 1 variant will carry at least 70t of payload to low Earth orbit (LEO), while the ultimate Block 2 variant will have a LEO payload of at least 130t. SLS is developing an interim Block 1B capability that employs a new, powerful upper stage – the Exploration Upper Stage (EUS) – that will yield a LEO payload of 105t. This unmatched heavy-lift ability enables reduced total mission duration time, greater mass to deep-space destinations, and reduced mission complexity and risk. The result is a launch vehicle that increases the probability of mission success.

Development is currently focused on the Block 1 configuration for the first integrated launch of SLS and the Orion crew spacecraft, which currently is planned as un-crewed flight beyond the moon. During this mission, 13 small CubeSat-class payloads will be transported into deep space to increase the scientific and technology outcomes while working to further NASA's exploration goals. Block 1 stands 98.2 meters (322 feet) tall and weighs 2.6 million kilograms (5.75 million pounds) full fueled. Liftoff thrust is more than 3.7 million kilograms (8 million pounds). The core stage provides liquid hydrogen and oxygen to four RS-25 engines. A pair of solid rocket boosters provides more than 75 percent of liftoff thrust. Second stage thrust is provided by the Interim Cryogenic Propulsion Stage (ICPS) based on the Delta Cryogenic Second Stage (DCSS). It is powered by a single Aerojet Rocketdyne RL10B-2 engine producing 24,750 pounds of thrust. The Block 1 vehicle is shown in Figure 2. Work is also underway on the Block 1B configuration, which is scheduled for the second integrated flight of SLS and Orion and will be the first crewed mission to the vicinity of the moon. The crew configuration of the Block 1B vehicle will also be capable of carrying large co-manifested payloads such as habitats or small landers, as well as a manifest of larger secondary payloads.

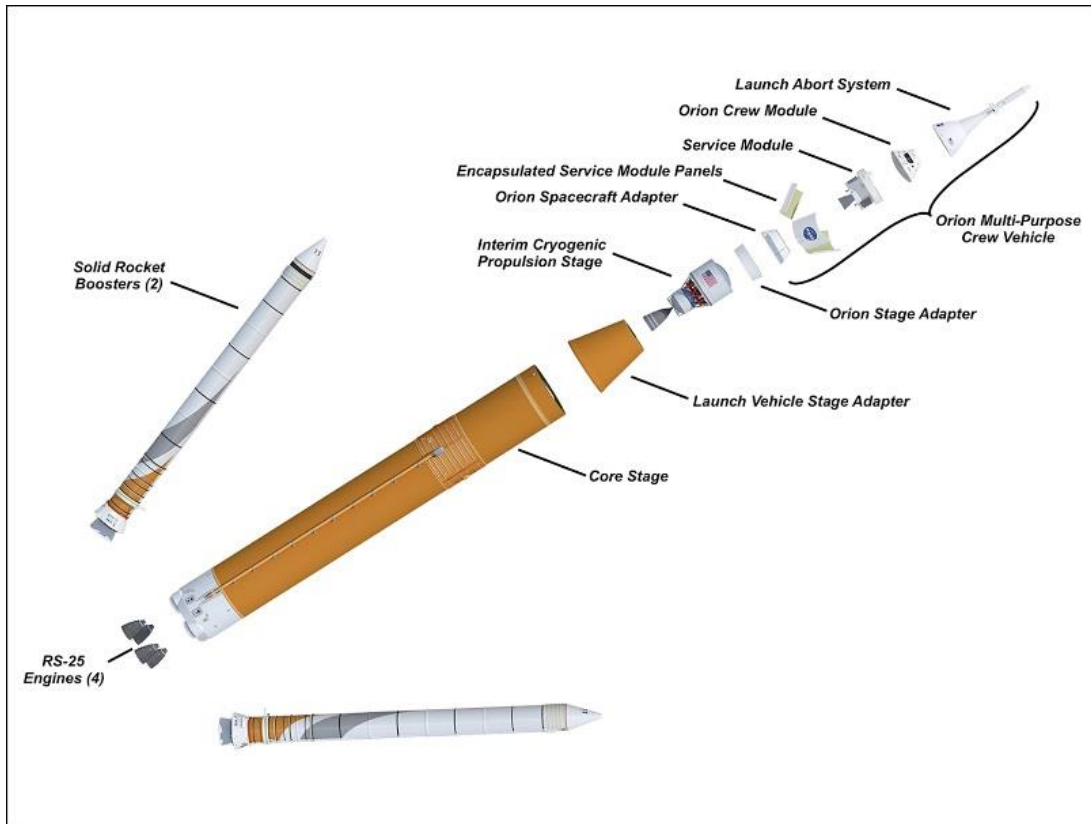


Figure 2: Major components of SLS Block 1 configuration.

CORE STAGE PROGRESS

Development and production of the SLS core stage accelerated in 2016 and continues in 2017. The core stage will be the largest rocket stage in the world, measuring 64.6m (212 feet) tall, 8.4m (27.6 feet) in diameter, and containing 2 million liters (537,000 gallons of cryogenic propellants). Key to manufacturing are six state-of-the-art welding tools for the core stage, including the world's largest spacecraft welding tool, the Vertical Assembly Center. At 170 feet tall, the Vertical Assembly Center is the last stop in welding the primary structure and is used to join the component rings, barrels and domes. Only the intertank is a bolted, rather than welded, structure.

To date, MAF workers have produced a series of test panels, weld confidence articles, structural test articles, and flight core stage hardware, developing experience and confidence with each step. Confidence articles verify that weld procedures are working as developed and tooling-to-hardware interfaces are correct. It also gives the weld team experience in bringing all aspects of hardware, tooling and software together. Qualification articles are flight-like hardware used for structural testing. An expanded view of core stage components is shown in Figure 3.

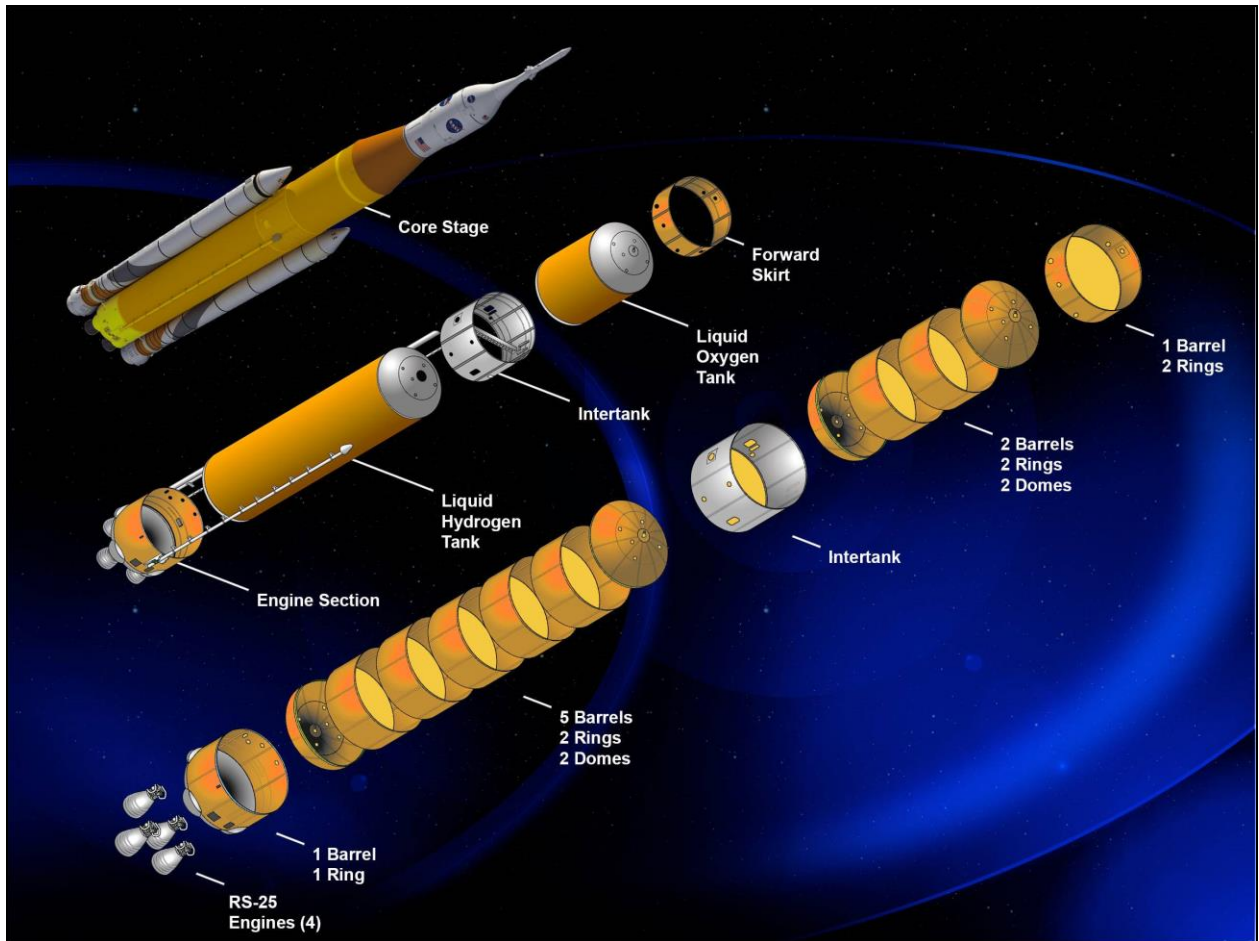


Figure 3: Expanded view of the core stage engine section, LH2 tank, intertank, LOX tank, and forward skirt, as well as their major subcomponent rings, domes and barrels.

As of mid-March, welding was completed on structural test articles for the engine section, liquid hydrogen tank and forward skirt. (Figure 4) Test articles are in various stages of equipment installation before shipment to MSFC for testing. Post-weld processing includes cleaning and priming, followed by wiring, plumbing and insulation. Indicative of this work is the installation of 45 miles of cables for data, power, video, and avionics, as well as vent lines, equipment shelves, propellant lines and couplings. The hydrogen qualification tank for structural testing successfully passed its initial pneumatic proof test in early 2017.¹

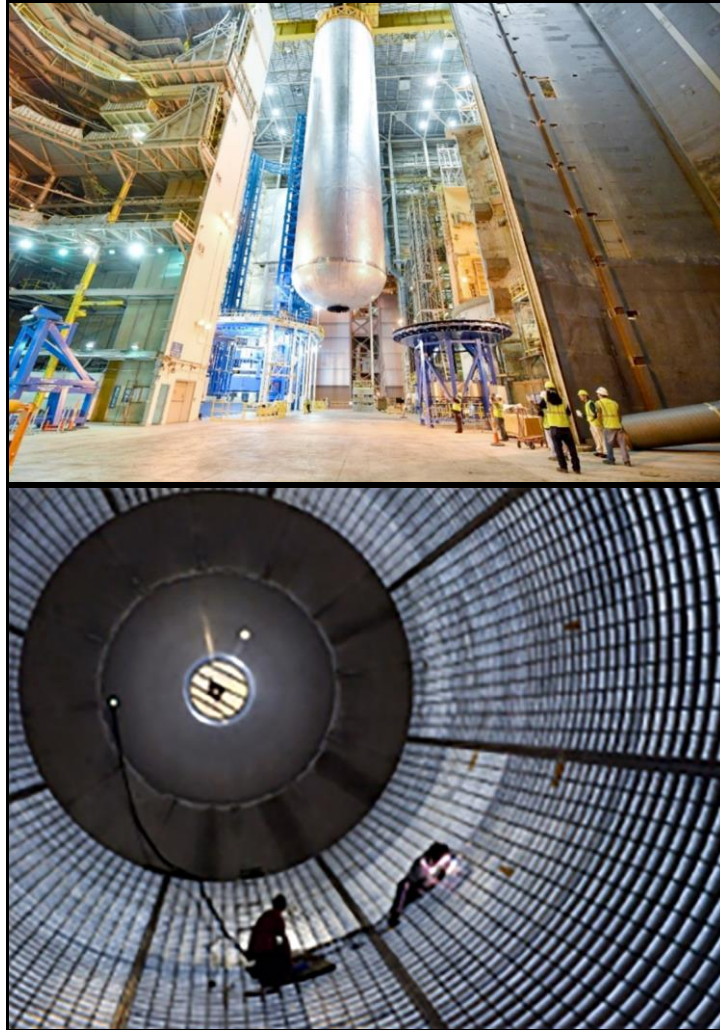


Figure 4: Major welding on the Vertical Assembly Center for the first SLS flight LH2 propellant tank was completed in September 2016. (top) Welders plug the holes at the start and end of each friction-stir weld where the pin tool entered and exited the hydrogen tank test article. (bottom)

Additionally, welding is complete on the flight hydrogen tank, engine section and forward skirt. Work is also underway on major components of the second flight core stage. With the LOX tank expected to require the thickest welds ever made with self-reacting friction stir welding, the Program decided in early 2017 to build a second LOX tank WCA, completed in March 2017, for analysis. Forward manufacturing work in 2017 includes the LOX structural test article and first flight LOX tank, as well as component welding for the second flight hydrogen and oxygen tanks, engine section and forward skirt.

The core stage pathfinder remains in work and is expected to be ready to ship to SSC and NASA's Kennedy Space Center (KSC) in early 2018, where it will be used for various transportation and fit checks.

No less important than manufacturing is structural testing to confirm the integrity of the design and manufacturing. The SLS core stage will be the largest rocket stage in the world. The LH2 tank, alone, is more than 130 feet tall and holds 537,000 gallons of LH2 cooled to minus 423 degrees F, which can cause the tanks to shrink several inches in length, in addition to the forces induced by stacking, roll-out, winds, and ascent.

Test Stands 4693 (LH2) and 4697 (LOX) were designed and developed by Marshall's Test Laboratory and the Office of Center Operations. The U.S. Army Corps of Engineers oversaw the construction contracts.

By late 2016 construction of the hydrogen and oxygen tank structural test stands at MSFC was completed,² and they were formally handed over to NASA for installation of cables, pipes, valves, control systems, cameras and lighting. (Figure 5)

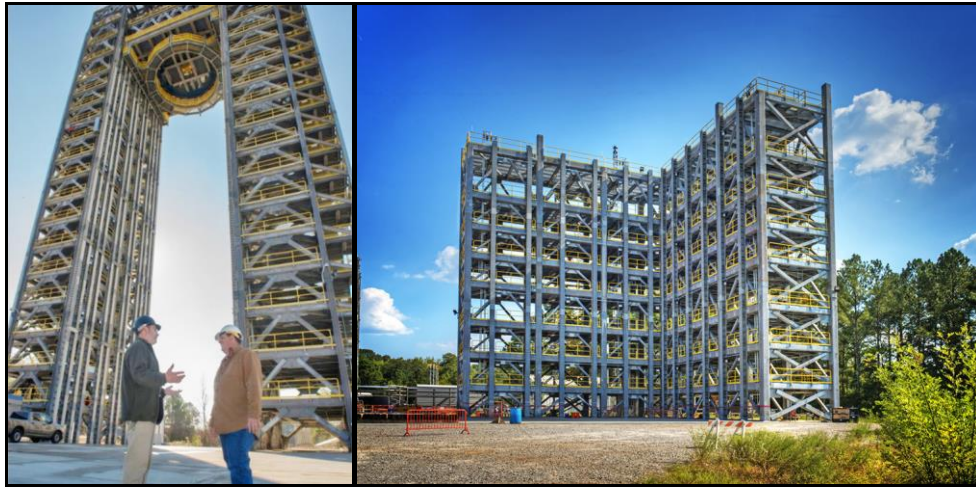


Figure 5: LH2 test stand left, and LOX test stand right following structural completion.

The twin-tower hydrogen structural test stand is more than 221 feet tall and is designed to be reconfigured to support other testing, including the EUS for Block 1B. The 149-foot-long test article LH2 test article includes fore and aft simulators and the LH2 tank. A total of 38 hydraulic cylinders will push and pull on the tank, including 24 at the base of the tank to simulate the thrust of four RS-25 engines. Compression loads up to 340,000 pounds and 340,00 pounds of shearing force can be simulated. More than 3,500 measurements will be captured in each of approximately 30 test scenarios. Testing is scheduled to begin in 2017.

The LOX test stand is an 85-foot-tall open structure. Load cells in the L-shaped test stand. The 70-foot test article will be subjected to up to nine million pounds of compressive forces and 300,000 pounds of shear loads.

The engine section is scheduled to arrive in the May timeframe and begin testing in fall 2017. The hydrogen tank test article completed proof pressure testing in March 2017. Additional test articles are expected to begin arriving in late 2017 and early 2018 for testing.

SOLID ROCKET BOOSTER PROGRESS

The SLS five-segment solid rocket booster is the largest ever designed and built for flight. Based on the space shuttle booster, it is 54m (177) feet long, 3.6m (12 feet) in diameter and weighs approximately 726t (1.6 million pounds). Each of SLS's two boosters generates approximately 3.6 million pounds of thrust during the first two minutes of flight.

Booster prime contractor Orbital ATK successfully conducted its second qualification motor test for SLS in June 2016. (Figure 6)³ A key objective of the 2016 test was performance of the booster structure and propellant under the minimum cold operating temperature of 40 degrees Fahrenheit (4 degrees Celsius.) The motor was instrumented with more than 530 sensors for the test. The two-minute, full-duration hotfire test provided NASA with data on 82

objectives that help pave the way for qualification. The 2016 full-scale static test followed a 2015 full-size test of a motor heated to the maximum planned operating temperature of 90 degrees Fahrenheit (32 degrees Celsius).

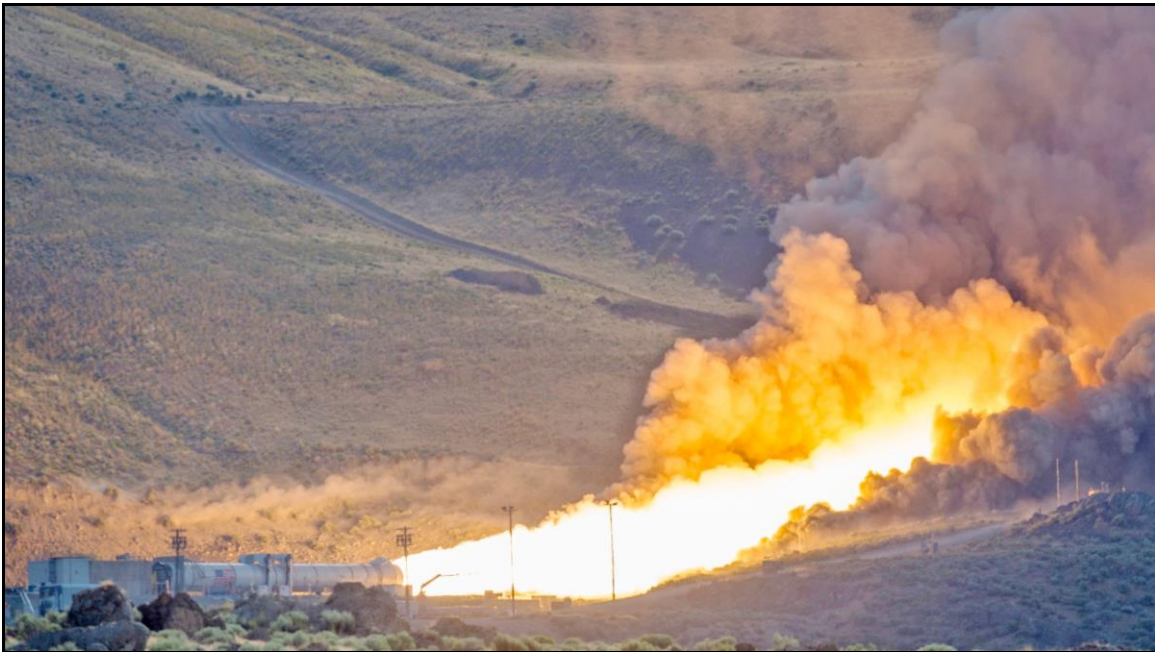


Figure 6: Qualification Motor 2 during hotfire testing in Utah desert.

Orbital ATK has to date cast eight solid rocket motor segments for the first integrated SLS/Orion mission, as well as the booster separation motors. Two of those segments have completed nondestructive evaluation and have been moved to storage, awaiting shipment to Kennedy Space Center.

The program plans to begin casting the solid rocket motors for the second mission in the summer of 2017. Booster separation motors for the second mission are already cast. The first flight igniter is installed in the left forward segment. In addition, aft exit cones for the first mission are in processing and well underway, with the left aft exit cone completely carbon-wrapped and machined. The right aft exit cone is beginning the wrapping process. The left-hand nozzle is also complete and will soon ship to Kennedy Space Center.

Orbital ATK technicians at Kennedy Space Center in Florida are outfitting forward and aft skirt assemblies for the first mission, performing such tasks as installing structural supports and the thrust vector control systems.⁴ The system-level qualification testing on booster avionics is underway at MSFC. Battery qualification is complete.



Figure 7: Forward skirt, top, and painted aft skirt, bottom, for the first SLS mission.

LIQUID ENGINES PROGRESS

The SLS core stage will be powered by four RS-25 engines. For SLS, engines will be operated at 109% of their rated thrust versus the 104.5% used for shuttle missions. Together they will provide more than 2 million pounds of thrust. Originally designed for the space shuttle in the 1970s, the RS-25 has been upgraded for reliability and safety throughout its life and remains one of the most efficient, powerful and proven engines in the world. NASA has enough shuttle-era RS-25 engines for the first four SLS missions, as well as two development engines.

In 2016 and 2017, the program continued to accumulate hotfire testing on the engines under SLS performance requirements, including higher inlet pressures colder temperatures, and exploration of the performance envelope under varying conditions. (Figure 8)



Figure 8: Drone camera captures rainbow created by an RS-25 engine test in February 2017.

The engine project marked two significant accomplishments in 2016 and early 2017. Engineers in 2016 test fired the first SLS flight engine, #2059, which will fly on the second SLS mission.⁵ Engines for the first SLS launch will be hot-fire tested as part of a complete hotfire test of the entire core stage on the B-2 stand at SSC in 2018. In early 2017, engineers also hotfire tested the first flight model (FM) of the new RS-25 Engine Control Unit (ECU) at SSC.⁶ The new controller replaces the heritage shuttle-era controller. Installed on development engine 0528, it was tested for 500 seconds. Two more flight engine controllers are scheduled for hotfire testing this year before being installed on flight engines. The fourth controller will be tested during the core stage green run test. ECU Flight Production Build 1 software was released on schedule and delivered to the RS-25 Hardware in the Loop Lab (HILL) in 2017 for formal verification and validation. Flight controllers are in full production, and lab testing is under way.

Development and production is also under way on re-starting RS-25 production. This will be a variant optimized for expendability and affordability. It will also be certified to operate at 111% of rated thrust. Hardware and processes related to reusability have been deleted. New tooling methods and 3D printing are reducing parts counts, production time and cost. As a result, the engine team is targeting a 30 percent reduction in engine cost. Aerojet Rocketdyne has produced a new main combustion chamber, powerhead, nozzle and many other components and completed an engine system-level design summary review in late 2016.

Ahead in 2017, the four flight engines for EM-1 will be transferred from SSC to MAF for integration into the core stage. The first flight model ECU is undergoing qualification testing at MSFC, while two more flight units will go to SSC for hotfire testing.

UPPER STAGE/PAYLOAD PROGRESS

In-Space propulsion for the Block 1 SLS will be provided by the Boeing Interim Cryogenic Propulsion Stage (ICPS) powered by a single Aerojet Rocketdyne RL10B LOX/LH2 engine. ICPS is based on the Delta Cryogenic Second Stage (DCSS) modified for SLS. ICPS will send Orion and 13 secondary payloads beyond the moon on the EM-1 mission. The original engine design dates to the early 1960s and has flown more than 400 missions and logged some 15,000 hot fires and more than 2.3 million seconds of operating time.

In November 2016, engineers lifted the ICPS test article in a 65-foot-tall structural test stand at MSFC as part of the Integrated Structural Test (IST). (Figure 9) The IST test article consists of the Launch Vehicle Stage Adapter, Frangible Joint Assembly, ICPS, Orion Stage Adapter (OSA), and Orion and core stage simulators.⁷ The test campaign in 2017 calls for approximately 50 different test cases.

United Launch Alliance has completed the flight-model ICPS for the first SLS launch and delivered it in February 2017 to Cape Canaveral Air Force Station for integration.⁸ It is the first integrated piece of SLS hardware to go to Florida for final processing and testing before moving to Ground Systems Development and Operations at KSC. ICPS is designed and built by ULA in Decatur, AL.



Figure 9: ICPS simulator lifted into the IST test stand at MSFC, top, and ICPS flight unit at ULA, Decatur, AL.

Janicki Industries, Hamilton, Washington, completed major assembly of the composite diaphragm for the Orion Stage Adapter in October 2016. (Figure 10) The adapter will join the Orion spacecraft to the ICPS for the first SLS mission.⁹ The adapter diaphragm is used to keep launch vehicle gases away from the spacecraft. Work also continues on payload accommodations for 13 suitcase-sized CubeSat secondary payloads carried and launched from the OSA. Secondary payload deployment system hardware is undergoing testing, including cable harnesses and avionics.



Figure 10: Technicians position composite layers of the diaphragm for the OSA.

BLOCK 1B PROGRESS

SLS also continues to make progress on the 1B variant. Compared to the 322-foot height of the Block 1, the Block 1B crew configuration is 364 feet tall, and the baseline 1B cargo variant is 327 feet tall. NASA completed the Preliminary Design Review (PDR) for the Block 1B Exploration Upper Stage (EUS) in early 2017 and is now working toward Critical Design Review.¹⁰ The review clears the way to start developing components and materials for the stage and building up tooling. EUS is a dual-use upper stage that will increase SLS payload mass from roughly 70 mt to 105 mt. EUS will replace the ICPS. The larger EUS will use four RL10 engines instead of the ICPS' one RL10. It also uses an 8.4-meter diameter liquid hydrogen tank and 5.5 meter diameter liquid oxygen tank. A new Universal Stage Adapter (USA) will connect the EUS to Orion and will be capable of carrying large co-manifested payloads, such as habitat modules, landers or other cargo. It will be manufactured at Michoud Assembly Facility and tested at the Stennis and Marshall field centers on the same welding tools, structural test facility, and stage test stand used to build and test the core stage. In 2016, NASA contracted with Aerojet Rocketdyne for production of 10 RL10C-3 engines for the second and third SLS missions, as well as two spare engines.

Other early work on Block 1B has included wind tunnel buffet testing at Langley Research Center that was focused on flight from transonic to supersonic to verify computer models. (Figure 11) Additional testing examined the effects of buffeting on the 1B cargo version caused by sound waves. Further tests are planned for 2017 and include transonic shock and oscillation on the 1B crew version. Observing the shock waves in the physical environment is important because their behavior is difficult to predict with computer models. Langley is also testing booster separation in early 2017 and liftoff transition testing in the summer of 2017. Wind tunnel tests at Ames Research Center assessed 1B performance during ascent through the transonic regime, including the instructions programmed into the flight computer for guidance and control.¹¹



Figure 11: A Langley engineer inspects a 1.3 percent scale model of Block 1B in a wind tunnel at Ames Research Center using a new pressure-sensitive paint that indicates air pressure.

FUTURE WORK

At the time this paper was in draft, NASA was evaluating options and issues around the possibility of adding crew to the first flight of SLS and Orion.¹² Acting Associate Administrator Robert Lightfoot announced in February 2017 that he had asked Associate Administrator for Human Exploration and Operations Mission Directorate William Gerstenmaier to conduct a study of the technical feasibility, risks, benefits, additional work required, resources needed and any associated schedule impacts of launching two crew members in mid-2019. It would likely use the existing crewed flight's eight-day mission profile with a multi-translunar injection/free return trajectory. As a starting condition, NASA would maintain the ICPS for the first flight.

SUMMARY AND CONCLUSIONS

The world's most capable launch vehicle is taking shape at manufacturing and test facilities around the U.S. It is designed specifically to support the most challenging national deep space human and scientific exploration missions and will be tested, certified and operated accordingly. Experience gained to date in development of the Block 1 variant will also apply to the evolved Block 1B and Block 2 vehicles at they mature. (Figure 12) SLS represents an enabling capability for many missions and significantly decreases risk and increases the opportunity for mission success for the nation's most important civil space missions.

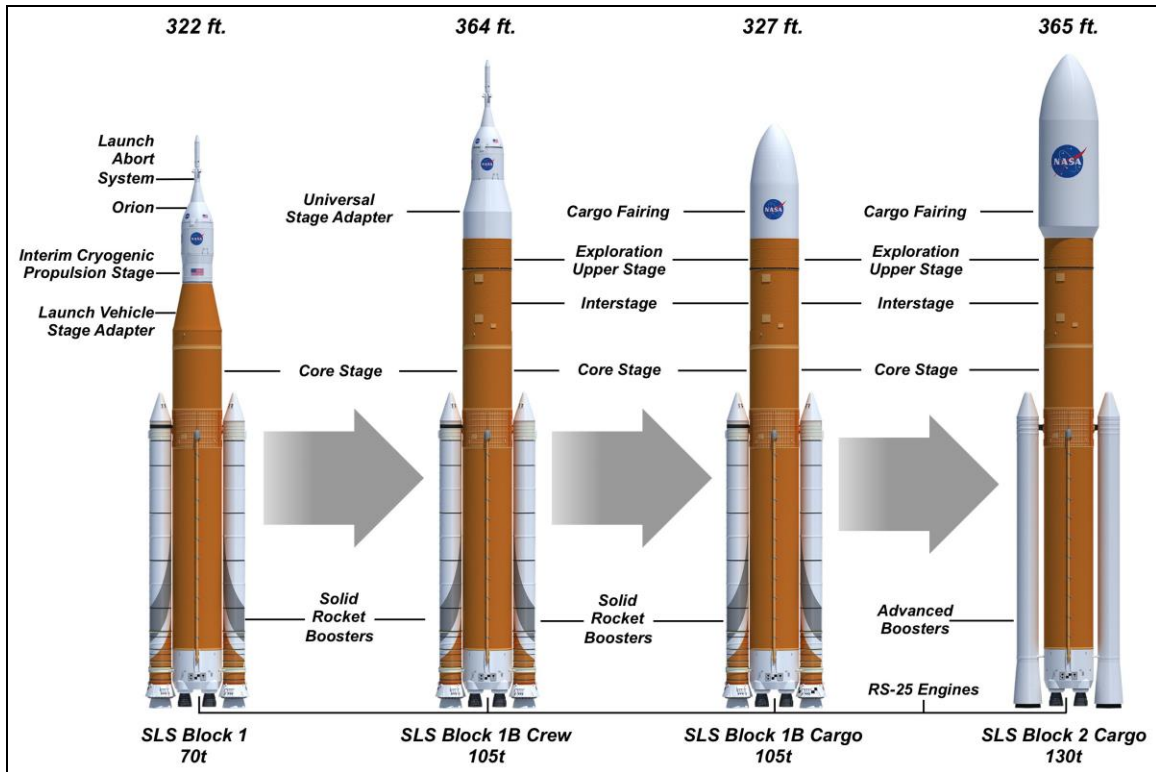


Figure 12: The SLS launch vehicle evolution showing (L-R) Block 1, Block 1B, Block 1B Cargo, and Block 2 Cargo.

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